

A discussion of CPV sensitivity in presence of NSI at DUNE and other long baseline experiments

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HRI

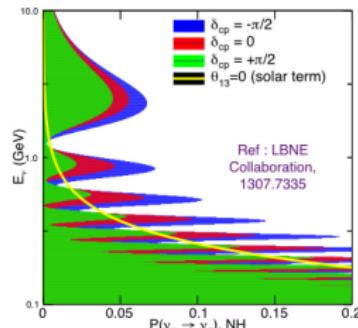
Based on arXiv:1603.01380 (MM, P. Mehta)

Motivation

CP violation in appearance channel@DUNE

$$P_{\mu e} = P_{atm} + P_{int}(\delta) + P_{sol}$$
$$\theta_{13}^2 \quad \theta_{13} \quad \theta_{13} - \text{indep}$$

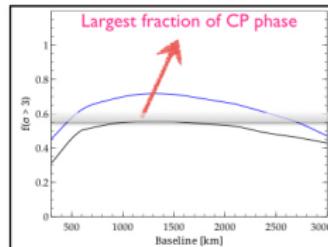
$$P(\nu_e \rightarrow \nu_\mu) = 4 \frac{(\Delta m_{31}^2)^2}{(\Delta m_{31}^2 - a)^2} s_{23}^2 s_{13}^2 \sin^2 \left(\frac{(\Delta m_{31}^2 - a)L}{4E} \right)$$
$$+ 8J_r \frac{\Delta m_{31}^2 \Delta m_{21}^2}{a(\Delta m_{31}^2 - a)} \sin \left(\frac{aL}{4E} \right) \sin \left(\frac{(\Delta m_{31}^2 - a)L}{4E} \right) \cos \left(\delta - \frac{\Delta m_{31}^2 L}{4E} \right)$$
$$+ 4 \left(\frac{\Delta m_{21}^2}{a} \right)^2 c_{12}^2 s_{12}^2 c_{23}^2 \sin^2 \left(\frac{aL}{4E} \right).$$



$$\frac{L(\text{km})}{E_\nu(\text{GeV})} = (2n - 1) \frac{\pi}{2} \frac{1}{1.27 \times \Delta m_{31}^2(\text{eV}^2)}$$
$$\approx (2n - 1) \times 510 \text{ km/GeV}$$

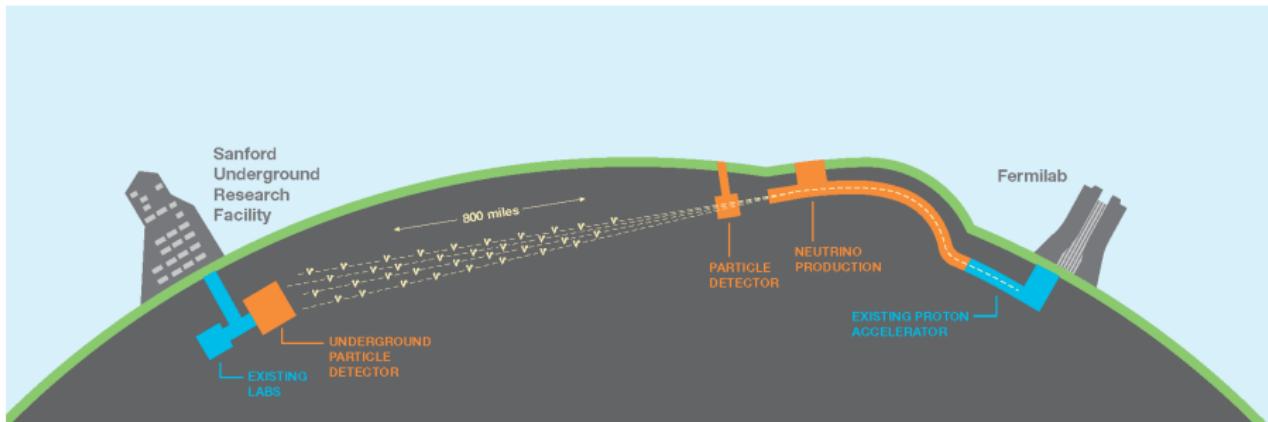
For E=2.5 GeV, we get L=1300 km

Ref : M. Masud, A. Chatterjee, P. Mehta, 1510.08261 ;
M. Masud and P. Mehta, 1603.01389



Slide from P. Mehta's talk

What is DUNE (Deep Underground Neutrino Experiment)?



- A proposed long baseline experiment (the erstwhile LBNE)
- 1300 km baseline
- Underground Far detector possibly augmented with a near detector

DUNE collaboration: 1512.06148

New physics (Non-standard neutrino interaction)

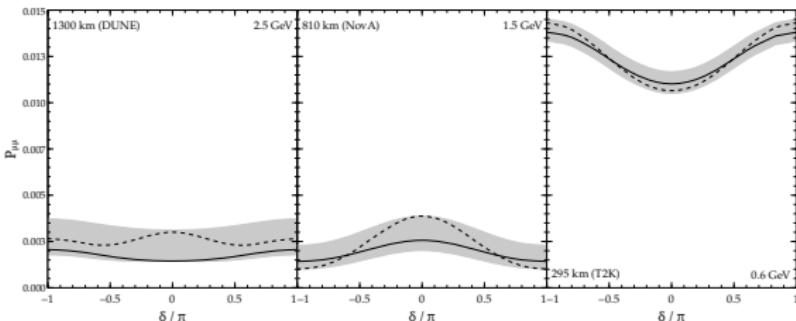
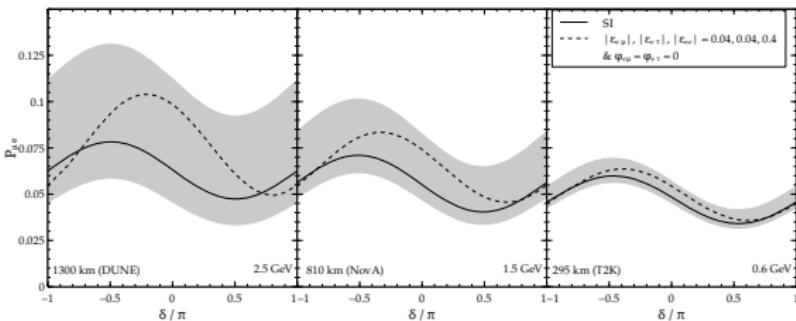
- $H = H_{vac} + H_{SI} + H_{NSI}$

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$|\varepsilon_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.3 & 0.5 \\ 0.3 & 0.068 & 0.04 \\ 0.5 & 0.04 & 0.15 \end{pmatrix}$$

1209.2710, 0907.0097, SK+MINOS collaboration

Effect of NSI phase variation : Probability level

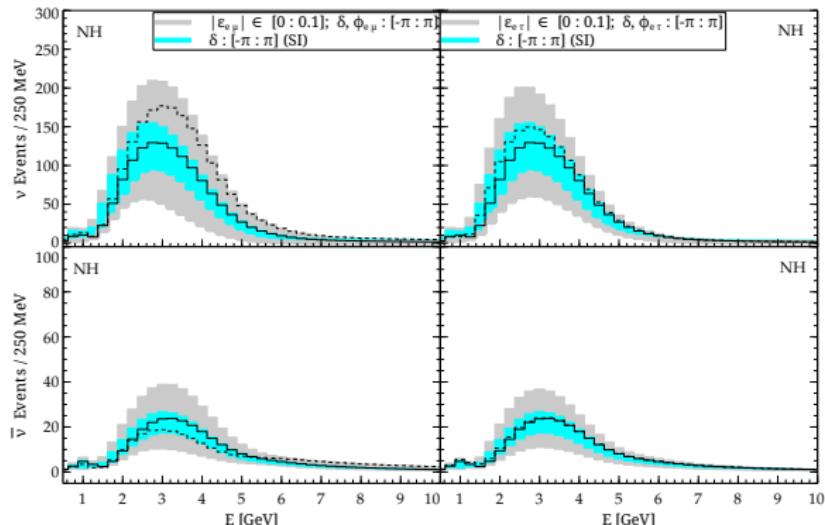


$$P_{\mu e} = a_{\mu e} + b_{\mu e} \sin \delta + c_{\mu e} \cos \delta$$
$$P_{\mu\mu} \simeq a_{\mu\mu} + c_{\mu\mu} \cos \delta$$

Simulation details

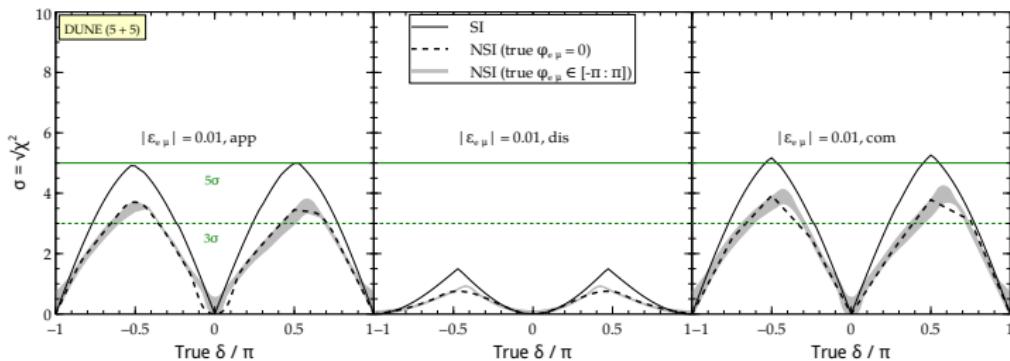
- DUNE: 1MW proton beam; (5+5) yrs of ($\nu + \bar{\nu}$) beam; 35 kt FD, 1300 km
- NOvA: 700 kW proton beam, 14 kt FD, 800 km, (3+3) yrs of ($\nu + \bar{\nu}$) beam
- T2K: 770 kW proton beam, 22.5 kt FD, 295 km, (3+3) yrs of ($\nu + \bar{\nu}$) beam
- HK: 7.5 MW proton beam, 560 kt FD, 295 km, (1+3) yrs of ($\nu + \bar{\nu}$) beam

Individual NSI: Impact on events at DUNE



Substantial overlapping regions: can come from SI or NSI-SI interplay

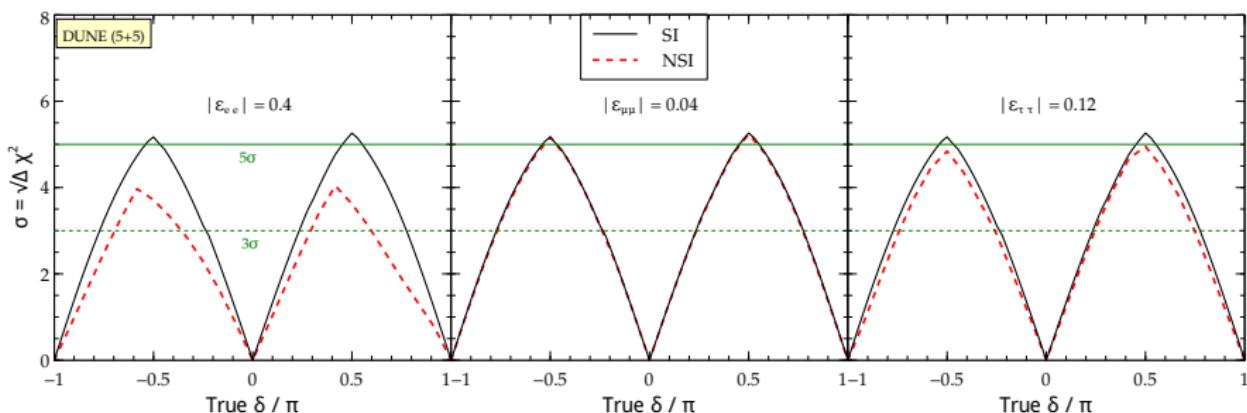
Effect of individual NSI on CPV sensitivity at DUNE



- χ^2 measures the contrast between:
 - the dataset containing δ_{true} ($\in [-\pi : \pi]$)
 - dataset containing the CP conserving cases ($0, \pi$)

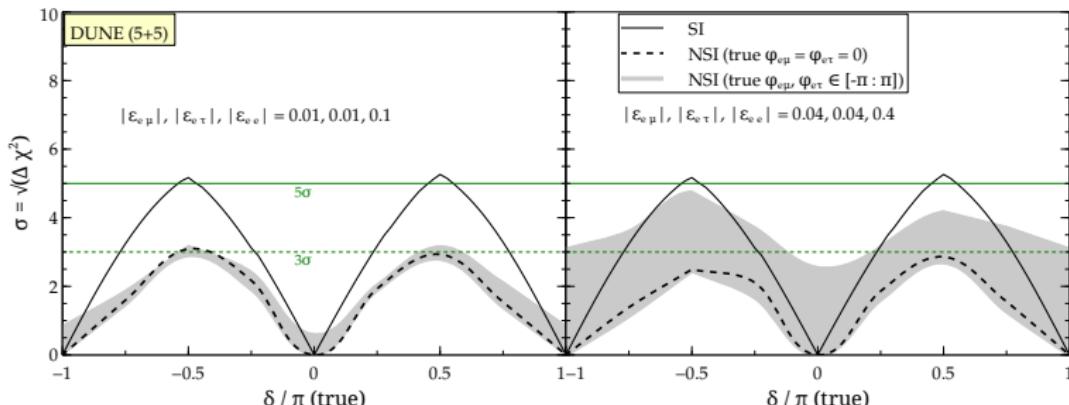
$$\begin{aligned}\bullet \quad & \chi_{\text{tot}}^2 = \min[\chi_{\text{app}}^2 + \bar{\chi}_{\text{app}}^2 + \chi_{\text{dis}}^2 + \bar{\chi}_{\text{dis}}^2] \\ & \propto \min_{0,\pi} \left\{ [b_{\mu e} \sin \delta_{\text{true}} + c_{\mu e} \cos \delta_{\text{true}} - c_{\mu e} \cos \delta|_{0,\pi}]^2 \right. \\ & \quad \left. + [c_{\mu\mu} \cos \delta_{\text{true}} - c_{\mu\mu} \cos \delta|_{0,\pi}]^2 + [\bar{\nu} \text{ terms}] \right\}\end{aligned}$$

Effect of diagonal NSI



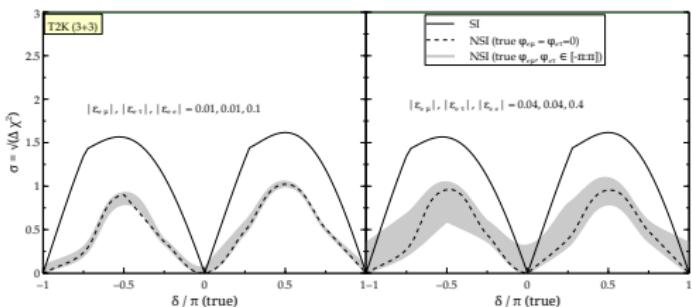
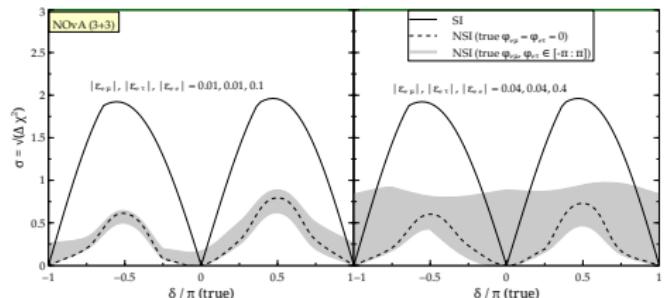
ϵ_{ee} has reasonable effect while $\epsilon_{\mu\mu}, \epsilon_{\tau\tau}$ have very small impacts (because of tight constraints)

Effect of collective NSI on CPV sensitivity at DUNE



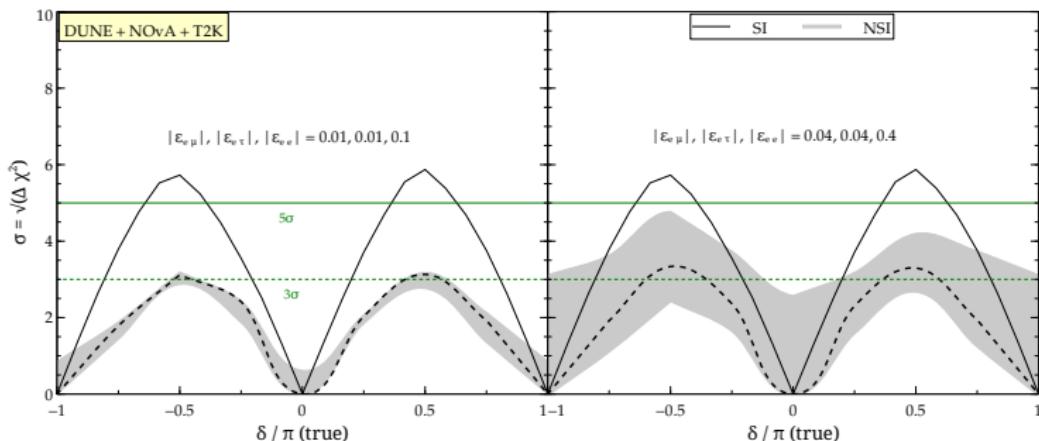
- Significant change in sensitivity in the NSI scenario.
- Can give misleading high sensitivity even for the CP conserving value $(0, \pi)$. Conversely, the introduction of NSI may also give $\lesssim 3\sigma$ sensitivity for the maximally CP violating values.

Effect of collective NSI on CP sensitivity at NOvA, T2K



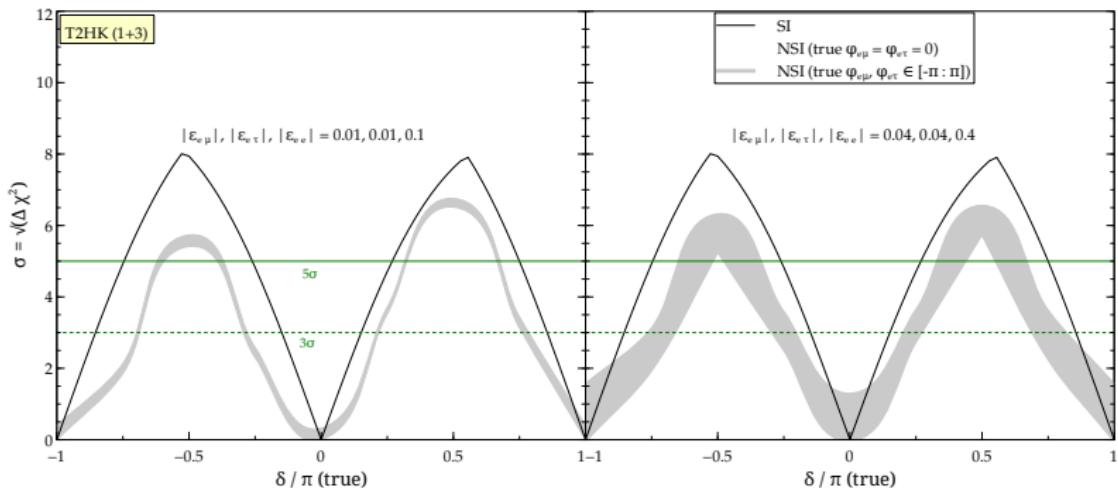
- Effect of NSI decreases as the baseline decreases

Effect of NSI on CPV sensitivity at DUNE + NOvA + T2K (combined)



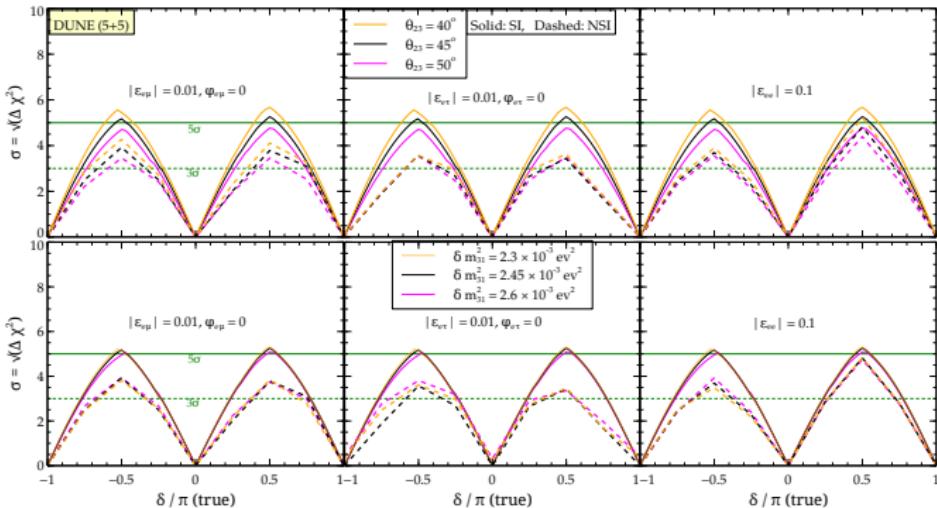
- The information from NOvA, T2K can serve in increasing the CP sensitivity at DUNE for the standard case
- The effect of NSI is grossly similar to that of DUNE even in the combined case

Effect of NSI on CPV sensitivity at HK



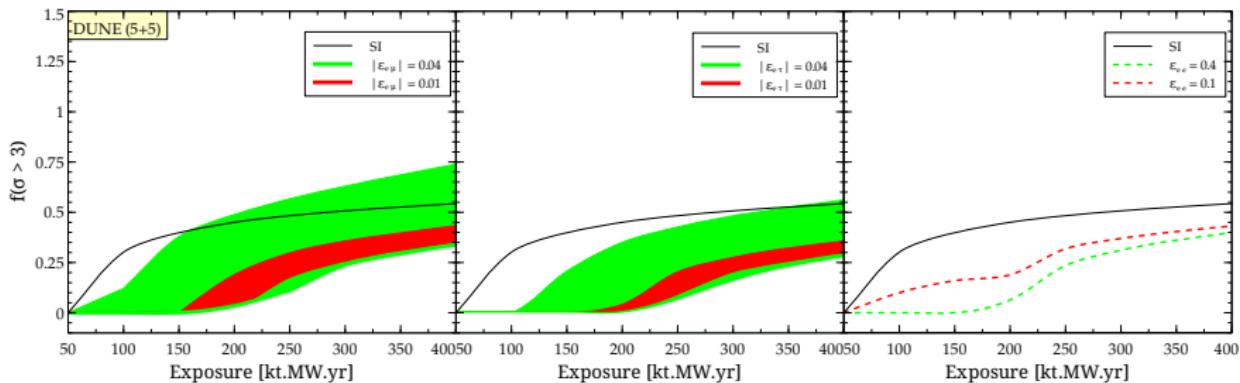
- 560 kt fiducial mass and 7.5 MW proton beam
- Although comparable to DUNE, the effect of NSI is much less due to shorter baseline

Choice of true values of Δm_{31}^2 and θ_{23}



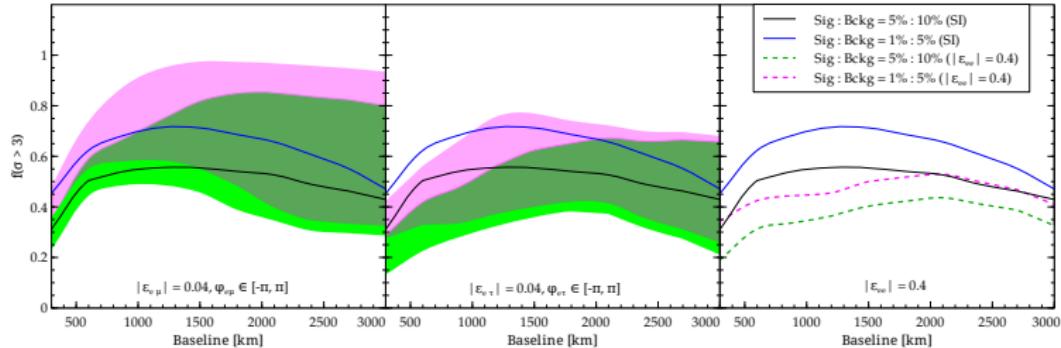
- Different choices of true θ_{23} has small effect
- Different true values of Δm_{31}^2 practically do not affect the CPV sensitivity

CP fraction and NSI



- In standard case, CP cannot be resolved above 3σ for about $\sim 55\%$ of the δ parameter space because the χ^2 is close to 0 at the CP conserving values $(0, \pm\pi)$
- NSI can drastically change this fraction
- In particular, a very small CP fraction even for a sufficiently large exposure (~ 250 kt.MW.yr) is an indication of new physics

Impact of NSI on baseline optimization



NSI term	Nominal systematics (green)		Optimal systematics (magenta)	
	NSI	SI	NSI	SI
	L_{opt} km	L_{opt} km	L_{opt} km	L_{opt} km
$ \varepsilon_{e\mu} = 0.04$	1800 – 2500 800 – 1300	1300	1500 – 3000 800 – 1300	1300
$ \varepsilon_{e\tau} = 0.04$	2000 – 3000 1800 – 2000	1300	1300 – 1500 1800 – 2000	1300
$\varepsilon_{ee} = 0.04$	1900 – 2100	1300	1900 – 2100	1300

Choice of baseline is significantly impacted by NSI!

Conclusion

- Introduction of NSI can significantly impact CPV sensitivity at long baselines and may even create confusion between CPV and CPC cases
- The effect of NSI increases with baseline and the impact also depends on the choice of detector
- The CP fraction serves as a useful quantity to probe new physics effects
- Finally the optimized choice of baseline (~ 1300 km) for DUNE can significantly change if NSI is present